

The decay of singlet scalar dark matter to unparticle and photon

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Abstract

We consider the unparticle physics introduced by Georgi and show that if the standard model is extended to include a singlet scalar as a dark matter candidate, there is a channel which leads to its decay to photon and unparticle. We calculate the decay rate for this new channel and find a lower bound on unparticle physics scale by demanding the stability of this candidate of the dark matter.

The unparticle physics suggested by Georgi [1] is related to the low energy physics of a non-trivial scale invariant sector which cannot be described by particles. However the concept of unparticle is understood via considering it as a tower of massive particles in which the mass spacing parameter goes to zero [2]. The infrared operators of the unparticle sector can be coupled effectively to the particle operators which are singlet under the standard model (SM) gauge group, through the following nonrenormalizable interactions:

$$\frac{\lambda}{\Lambda^{d_p+d_u-4}} \mathcal{O}_p \mathcal{O}_u, \quad (1)$$

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where the subscripts p and u refer to particle and unparticle, respectively. In this way d_p and d_u are respectively mass dimension of \mathcal{O}_p and \mathcal{O}_u and Λ is the unparticle sector scale. The phenomenological aspects of unparticle physics have recently been studied extensively in the literature such as [3, 4].

On the other hand, there are some convincing evidences that 80% of the matters in the Universe is composed of neutral and weakly interacting elementary particles which are called dark matters (DM). The candidate for this type of matter cannot be accommodated in the SM. Therefore there are various models that incorporate either fermionic or bosonic candidates for the DM in addition to the SM particles. If we suppose the DM candidates are in thermal equilibrium during freeze out, their relic abundance depends on their annihilation cross sections and therefore their mass scale is constrained as [5]:

$$m_{DM} \leq 340 TeV. \quad (2)$$

Meanwhile, superheavy candidates ($m_{DM} \geq 10^{10} GeV$) are also possible, provided that we ignore the thermal equilibrium condition [6].

Adding a singlet scalar to the SM is a simple method to have DM [7]. The extreme smallness of the DM coupling causes it to be stable. Meanwhile by introducing a new symmetry similar to R-symmetry in the MSSM, we can guarantee the stability of the DM. For instance, if one considers the electroweak fermions including left handed electroweak doublets and right handed singlets are supplemented by mirror partners including right handed doublet and left handed singlet, the following coupling can occur:

$$\phi(C_l \bar{f}_L F_R + C_r \bar{f}_R F_L) + h.c. , \quad (3)$$

where ϕ is a singlet scalar, C_l and C_r are coupling constant, f_L and f_R are left handed doublet and right handed singlet electroweak fermions and F_R and F_L are respectively their mirror partners, either ϕ or F_R and F_L which are odd under a supposed Z_2 symmetry in contrary to SM particles, can play the role of the DM candidate [8]. Moreover, since we do not have any experimental evidence for observing the mirror partners, their mass scale must be more than about 100 GeV at least. Similarly, if one considers a Z_2 discrete symmetry, under which the unparticle stuffs are odd while the SM particles are even, the unparticle stuffs can also be new candidates of the DM [9].

Nevertheless, if we consider both the unparticle stuffs and DM particles are odd under a supposed Z_2 symmetry while the SM particles are even, the decay of DM to an unparticle stuff and SM particles is permissible. In this letter, we suppose an extension of the SM where a gauge singlet scalar is nominated as DM and then study the decay rate of this candidate to a vector unparticle stuff and photon. However, the stability of

DM particles implies that their lifetime must be greater than the age of the Universe ($4.5 \times 10^{17} s$). Using this fact we obtain some lower bounds on unparticle scale.

All possible interactions between the SM operators and various unparticle ones have already been written in [4]. However, if the SM is extended to incorporate new particles, consequently, we can have more interactions in this scenario such as the following terms which are relevant for our purpose:

$$\frac{\lambda_1}{\Lambda^{d_u}} \phi F_{\mu\nu} \partial^\mu \mathcal{U}^\nu + \frac{\tilde{\lambda}_1}{\Lambda^{d_u}} \phi \tilde{F}_{\mu\nu} \partial^\mu \mathcal{U}^\nu, \quad (4)$$

where ϕ and $F_{\mu\nu}$ ($\tilde{F}_{\mu\nu}$) are the SM singlet scalar field and the photon strength tensor (dual corresponding one), respectively. In (4), we have supposed that the unparticle operator is a conserved current, $\partial_\mu \mathcal{O}_u^\mu = 0$. Therefore to conserve unitarity we have to take $d_u = 3$ [11]. This Lagrangian leads to the following Feynman rule:

$$\frac{\lambda}{\Lambda^{d_u}} (k_\mu \epsilon_\nu(\mathbf{k}) - k_\nu \epsilon_\mu(\mathbf{k})) p^\mu \epsilon'_\nu(\mathbf{p}) + \frac{\tilde{\lambda}}{\Lambda^{d_u}} \varepsilon_{\mu\nu\rho\sigma} (k^\rho \epsilon^\sigma(\mathbf{k}) - k^\sigma \epsilon^\rho(\mathbf{k})) p^\mu \epsilon'_\nu(\mathbf{p}) \quad (5)$$

in which the ϵ 's, (ϵ_u 's) and k 's (p 's) are polarization and momentum four vector for photon (unparticle), respectively. As the most straightforward result of the new coupling (4), a SM singlet scalar which may be considered as a DM candidate [7], can decay to a photon and a vector unparticle, $\phi \rightarrow \gamma + \mathcal{U}$.

The differential decay rate can be written as follows:

$$d\Gamma = \frac{|\mathcal{M}|^2}{2M} d\Phi, \quad (6)$$

where $d\Phi$ denotes the phase space factor and according to selected normalization in [1] is:

$$d\Phi(P) = \int (2\pi)^4 \delta^4(P - k - p) d\Phi_\gamma(k) d\Phi_u(p) \frac{d^4 p}{(2\pi)^4} \frac{d^4 k}{(2\pi)^4}. \quad (7)$$

The final state densities corresponding to photon and an unparticle vector, respectively, are

$$\begin{aligned} d\Phi_\gamma(k) &= 2\pi \theta(k_0) \delta(k^2), \\ d\Phi_u(p) &= A_{d_u} \theta(p_0) \delta(p^2) (p^2)^{d_u-2}, \end{aligned} \quad (8)$$

in which

$$A_{d_u} = \frac{16\pi^{5/2}}{(2\pi)^{2d_u}} \frac{\Gamma(d_u + \frac{1}{2})}{\Gamma(d_u - 1)\Gamma(2d_u)}. \quad (9)$$

Therefore the differential decay rate for $\phi \rightarrow \gamma + \mathcal{U}$ as a function of photons energy becomes:

$$\frac{d\Gamma}{d\omega} = \frac{A_{d_u}}{\Lambda^{2d_u}} \frac{|\lambda|^2 - 4|\tilde{\lambda}|^2}{4\pi^2} M\omega^3 \theta(M - 2\omega) (M^2 - 2M\omega)^{d_u-2}, \quad (10)$$

| | | | | | |
|-----------------------|-------------------|-------------------|-------------------|-------------------|----------------------|
| M (on GeV) | 10^{-3} | 1 | 10^2 | 10^3 | 10^5 |
| Λ (on GeV) | 1.2×10^2 | 3.7×10^5 | 8.1×10^7 | 1.2×10^9 | 2.5×10^{11} |

Table 1: The lower bound on unparticle scale obtained from the decay of a singlet scalar DM, which is in thermal equilibrium during freeze out.

where the step function $\theta(M - 2\omega)$ forbids decaying when dark matter mass is less than the twice of the energy of photon, which is logical by kinematical reality. Consequently, the total decay rate is obtained as:

$$\Gamma = \frac{3A_{d_u}}{d(d^2 - 1)(d + 2)} \frac{|\lambda|^2 - 4|\tilde{\lambda}|^2}{32\pi^2} \frac{M^{2d_u+1}}{\Lambda^{2d_u}}. \quad (11)$$

Here we consider the coupling constant, $|\lambda|^2 - 4|\tilde{\lambda}|^2$, is of the order of one. We demand the lifetime of the DM candidates be greater than the lifetime of the Universe. So in this way, we obtain lower bounds on the unparticle scale. These bounds depend on the mass scale of the DM. However if we suppose that the singlet scalar DM was in thermal equilibrium during freeze out, according to the table (1) the most stringent bound on unparticle scale is in the order of $10^{11}GeV$. Otherwise, for the superheavy DM candidate, i.e. $M \sim 10^{12}GeV$, the obtained lower bound on unparticle scale is of the order of $10^{19}GeV$.

In summary, in this letter we purpose an extended SM in which there is a gauge singlet scalar that plays the rule of the DM candidate. Then considering the unparticle physics suggested by Georgi, we investigate the decay of this candidate due to this new physics. So at first, we write a gauge invariant coupling of the singlet scalar DM with a vector unparticle and photon. Then we calculate the decay rate of the singlet scalar DM to vector unparticle and photon. Demanding the lifetime of the DM candidate be greater than the age of the Universe, we obtain the lower bound on the unparticle scale. This obtained lower bound for unparticle depends on the DM mass. The more DM mass makes more stringent lower bound on the unparticle scale. If the mass of scalar DM is about $10^{-3}GeV$ to 10^5GeV which is permissable if the DM candidates are in thermal equilibrium during freeze out, the unparticle scale is about 10^2GeV to $10^{11}GeV$. For the superheavy candidate whose mass scale is about $10^{12}GeV$, the unparticle scale is obtained to be about $10^{19}GeV$.

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